Astronomy & Astrophysics manuscript no. letter
February 3, 2008
© ESO 2008

arXiv:astro-ph/0603341v1 14 Mar 2006

Letter to the Editor

Detectability of dirty dust grains in brown dwarf atmospheres

Ch. Helling[1], W.-F. Thi[1,3], P. Woitke[2], and M. Fridlund[1]

[1] Research and Scientific Support Department, ESTEC/ESA, P.O. Box 299, 2200 AG Noordwijk, The Netherlands
e-mail: chelling@esa.int
[2] Sterrewacht Leiden, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[3] Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK

February 1, 2006; March 11, 2006

ABSTRACT

Context. Dust clouds influence the atmospheric structure of brown dwarfs, and they affect the heat transfer and change the gas-phase chemistry. However, the physics of their formation and evolution is not well understood. The dust composition can be predicted from thermodynamical equilibrium or time-dependent chemistry that takes into account seed particle formation, grain growth, evaporation and drift.
Aims. In this *letter*, we predict dust signatures and propose a potential observational test of the physics of dust formation in brown dwarf atmosphere based on the spectral features of the different solid components predicted by dust formation theory.
Methods. A momentum method for the formation of dirty dust grains (nucleation, growth, evaporation, drift) is used in application to a static brown dwarf atmosphere structure to compute the dust grain properties, in particular the heterogeneous grain composition and the grain size. Effective medium and Mie theory are used to compute the extinction of these spherical grains.
Results. Dust formation results in grains whose composition differs from that of grains formed at equilibrium. Our kinetic model predicts that solid amorphous SiO_2[s] (silica) is one of the most abundant solid component followed by amorphous Mg_2SiO_4[s] and $MgSiO_3$[s], while SiO_2[s] is absent in equilibrium models because it is a metastable solid. Solid amorphous SiO_2[s] possesses a strong broad absorption feature centered at 8.7 μm, while amorphous Mg_2SiO_4[s]/$MgSiO_3$[s] absorb at 9.7 μm beside other absorption features at longer wavelength. Those features at $\lambda < 15\mu$m are detectable in absorption if grains are small (radius $< 0.2\,\mu$m) in the upper atmosphere as suggested by our model.
Conclusions. We suggest that the detection of a feature at 8.7 μm in deep infrared spectra could provide evidence for non-equilibrium dust formation that yields grains composed of metastable solids in brown dwarf atmospheres. This feature will shift towards 10μm and broaden if silicates (e.g. fosterite) are much more abundant.

Key words. brown dwarfs - spectral features

1. Introduction

Atmospheric models are essential in the interpretation of complex brown dwarfs spectra, which are dominated by strong molecular absorption lines. The physics and chemistry of substellar objects (brown dwarf and giant planets) are more complicated than anticipated because of non-equilibrium processes (dust formation, convective mixing) and their non-linear feedbacks on the radiative transfer. Consequently, parametrisations of processes like dust formation and convection were applied in atmospheric models so far. Current model atmospheres provide extensive solutions of the radiative transfer problem for the gas phase in hydrostatic equilibrium (Tsuji et al., 1996; Marley et al., 1996; Burrows et al., 1997; Allard et al., 2001). However, the presence of dust is at present only inferred from classical models, where the dust composition is derived from gas/solid phase equilibrium considerations and time-scale arguments, and their comparison to observed spectra (Lunine et al., 1989; Tsuji et al., 1996; Tsuji, 2002; Ackerman & Marley, 2001; Allard et al., 2001; Cooper et al., 2003). Such equilibrium chemistry results in grains with a homogeneous composition.

Considering the non-equilibrium character of phase transitions (supersaturation$\gg 1$), Woitke & Helling (2003, 2004) and Helling & Woitke (2006) proposed a theoretical approach to consistently model the formation of dust grains by nucleation (seed formation), growth, evaporation and drift (gravitational settling). In contrast to the phase-equilibrium calcula-

Send offprint requests to: Ch. Helling (chelling@esa.int)

tion, Woitke & Helling argue that grains in the oxygen-rich environment of a brown dwarf are heterogeneous in chemical composition and in size. Moreover, precipitating into the denser inner atmospheres, these particles can reach sizes of several 100 μm. In Helling & Woitke (2006), the inferred dust composition differs markedly from that predicted by equilibrium chemistry. These differences manifest in the intrinsic absorption signatures of the solids in the mid-infrared range.

This *letter* suggests a potential observational test for the presence of dust. The dust may be present in form of cloud-like structures. We will focus on the main characteristics of the theory, where the predictions in terms of dust spectral features can be tested with current and future instruments. In Sect. 2, we report on recent progress in modeling the formation of chemically non-homogeneous cloud layers made of dirty (i.e. a variety of compounds) grains in brown dwarf atmospheres. A detailed Mie theory treatment combined with effective medium theory allows us to suggest possible spectral features of such a dust layer for both approaches. The result of the modeling is described and discussed in Sect. 3

2. Approach

We model nucleation, heterogeneous growth, evaporation, and drift (gravitational settling) of dirty dust particles in a quasi-static atmosphere by the moment method (Helling & Woitke, 2006). Our prescription considers the formation of compact spherical grains in an oxygen-rich gas by the initial nucleation of TiO_2 seed particles followed by the growth of a dirty mantle made of various solids. We consider amorphous TiO_2[s], SiO_2[s], MgO[s], $MgSiO_3$[s], Mg_2SiO_4[s], Al_2O_3[s], and metallic iron Fe[s], assuming that silica and silicates have approximately the same sticking probability. The moment and elemental conservation equations for Ti, Si, Mg, Fe, Al, and O are evaluated on top of a prescribed static model atmosphere structure (Allard et al. [1]) without further iteration on the temperature profile. The model calculates the amount of condensates, the mean grain size $\langle a\rangle$, and the volume fractions V_s of each material as function of height z in the brown dwarf atmosphere for given model structures. At each depth in the atmosphere, the volumes fractions are used to compute mean dust optical constants using the Maxwell-Garnett effective medium theory (Bohren & Huffman, 1983), which is a valid method because the grains generally have one main volume component. The main dust component is the matrix in which the spherical inclusions made of the minor components are embedded. Dust extinction coefficients are subsequently computed using a Mie theory code for compact spherical grains. The different components are assumed in an amorphous state, consistent with laboratory experiments of heterogeneous dust formation (e.g., Rietmeijer et al. 1999). The optical constants for the amorphous solids are obtained from laboratory measurements (TiO_2[s]: Ribarsky (1985), $SiO2_{[s]}$: Henning & Mutschke (1997), MgO: Hofmeister et al. (2003), $MgSiO_3$[s]/Mg_2SiO_4[s]: Jäger et al. (2003), Al_2O_3[s]: Begemann et al. (1997), and Fe[s]: Ordal et al. (1985)). Absorption cross sections and optical depth are then derived using the dust density profiles assuming a grain size distribution $f(a,z) = \langle a(z)\rangle\,\delta(a - \langle a(z)\rangle)$. For comparison, similar computations were performed assuming that no SiO_2[s] can form by setting the formation rate to zero. We also estimate the possible absorption depth in observed spectra. The contrast between the depth of the features and the continuum is an important parameter for predicting the detectability of the dust features.

[1] adopted from ftp.ens-lyon.fr/pub/users/CRAL/fallard/

3. Results

We first show the grain size and dust composition profile of a AMES (cond) model with $T_{\rm eff}$ = 1500 K, log g= 5.0 ([1]) and solar element composition. This can be considered a typical late L-dwarf atmosphere model. The outputs are then used to compute the dust extinction coefficient in the mid-infrared.

3.1. Global grain size distribution and material composition

The results depicted in Fig. 1 show the same global dust cloud structure as presented in Woitke & Helling (2004). The formation of the cloud is governed by the hierarchical dominance of nucleation (upper most layers), growth & drift (intermediate layers), and evaporation & drift (deepest layers). The uppermost cloud layers are predominantly filled with small grains of a mean size of $10^{-2}\mu$m which grow on their way into the atmosphere to 200 ... 300 μm (l.h.s. Fig. 1). Eventually they enter even hotter atmospheric layers where they are no longer thermally stable. Hence, the grains shrink in size and finally dissolve into the surrounding hot and convective gas. This picture reflects the stationary character of the grain component forming the brown dwarf's dust cloud where dusty material constantly fall inward and fresh, dust-free material is mixed upward.

Table 1. Dust grain's mean size and material composition.

local temperature T [K]	mean grain size $\langle a\rangle$ [μm]	material composition [volume frac.]
$\lesssim$ 1000	10^{-2} ... 10^{-1}	25 – 35% SiO_2[s] 20 – 25% Mg_2SiO_4[s] 10 – 25% $MgSiO_3$[s] 15% Fe[s], 10% MgO[s]
1000 ... 1700	10^{-1} ... 30	25 – 30% Mg_2SiO_4[s] 20 – 30% $MgSiO_3$[s] & SiO_2[s] 15% Fe[s], 10% MgO[s]
1700 ... 2000	30 ... 200	strongly changing composition
2000 ... 2300	200 ... 300	80%Fe[s], ~ 18% Al_2O_3

The r.h.s. of Fig. 1 demonstrates the chemical composition of the dust grains. The grains are not of a single, homogeneous material composition and their material composition changes on their descent into the atmosphere. Since gas and dust thermalise faster than the dust growth/evaporation processes take

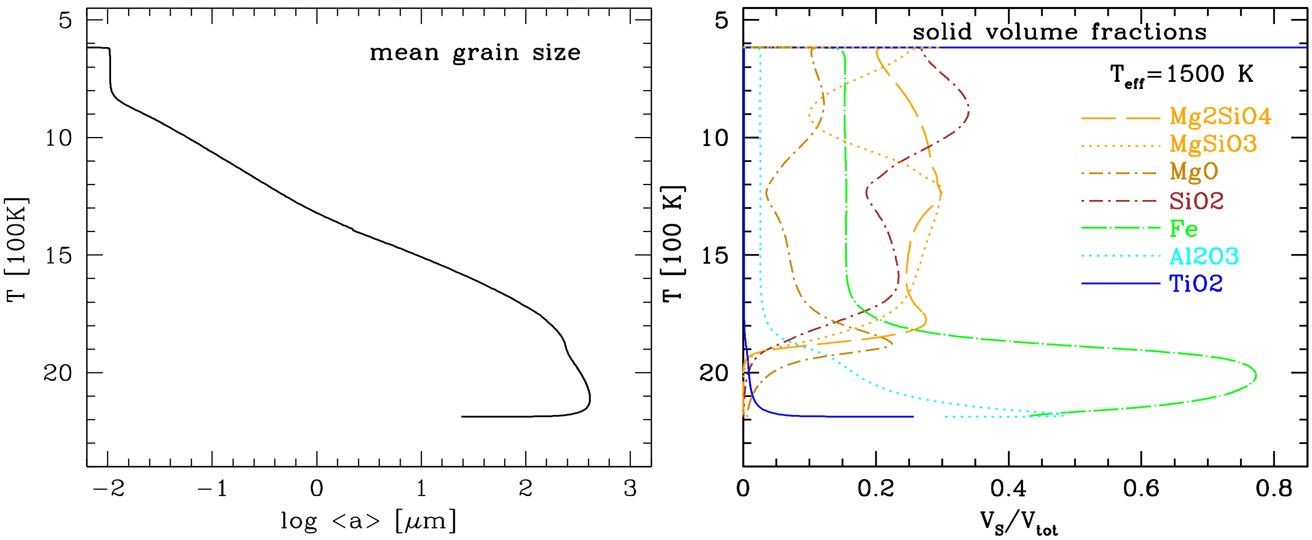

Fig. 1. Left: Mean grain size stratification for a plan-parallel AMES (cond) late L-type brown dwarf model atmosphere of $T_{\rm eff}$ = 1500 K, log g= 5.0 of original solar abundance. **Right:** Chemical material composition of the grains in volume fractions of the solids for the same model ($V^{\rm dust}_{\rm tot} = \sum_s V_s$, s – contributing solid materials). Note the upside-down scale of the local temperature T [100 K].

place (Woitke & Helling 2003), the chemical composition is determined by the local temperature and the reaction kinetics. Therefore, the upper atmosphere is populated by small, silica- and silicate-like grains until these materials become thermally unstable. Therefore in the lower and hotter part of the atmosphere big grains appear which are merely made of iron and some impurities of Al_2O_3[s] and TiO_2[s]. The main dust component in the upper part of the dust layer is amorphous SiO_2[s] followed by Mg_2SiO_4[s]/$MgSiO_3$[s] (see Table 1). The prediction contrasts with those from equilibrium dust formation models where metastable species such as SiO_2[s] cannot exist (e.g Lodders & Fegley 2005).

3.2. Spectral dust cloud features

Figure 2 depicts the resulting spectral features from 6 μm ... 15 μm for a brown dwarf dust cloud layer with the mean grain size and chemical dust material composition shown in Fig. 1.

For grain composition predicted by heterogeneous dust formation, the only dust features with an appreciable contrast are those of SiO_2[s] centered at 8.7 μm and of Mg_2SiO_4[s]/$MgSiO_3$[s] at 9.7 μm, with weaker absorption features around 20 μm and 32 μm (not shown). The features are broad (~ 1 – 1.5 μm) and lack substructures because the grains are amorphous. The abundance of metallic iron is high (~ 15%) but metals absorb photons continuously and do not show spectral features. The abundance of Al_2O_3[s] and TiO_2[s] in grains are too small to significantly affect the overall extinction coefficient. In models where SiO_2[s] is disregarded (dashed line, l.h.s. Fig. 2), the dust extinction is dominated by Mg_2SiO_4[s]/$MgSiO_3$[s] at 9.7 μm. The mean grain radius remains smaller than 0.2 μm in the $\tau_{\rm dust} < 1$ region in the model. Therefore, the grain absorption features remain. In contrast, if grains were a large as 10 μm, the resonance features would disappear (Min et al., 2004). The region where $\tau_{\rm dust} < 1$ in the wavelength range 5 – 25 μm has pressure below 10^{-2} bar in the model atmosphere considered.

In phase-equilibrium, the condensates are formed locally and retain the energetically most favorable composition at the temperature and pressure of the given depth in the atmosphere (Lodders & Fegley, 2005, in press). Further condensation is not possible because the grains remain in relative thin discrete cloud layers and, hence, can not move into regions with still favorable growth conditions. Individual cloud layers are composed of different solid species depending on the temperature of the layer. Above the silicate clouds, the gas phase is strongly depleted and thus the absence of gas-phase species in L and T dwarf atmosphere has been used as an evidence for the presence of clouds. The prediction of equilibrium theory is the absence of solid SiO_2, hence equilibrium-dust is predominately composed of silicates. We modeled the absence of SiO_2[s] and the spectral result is shown in Fig. 2 (l.h.s.). Beside moving the peak of the absorption to 9.7 μm, the absence of amorphous $SiO_{2[s]}$ decreases substantially the absorption contrast.

3.3. Discussion of detectability

We now discuss the detectability of infrared dust features in brown dwarf atmospheres. From Fig. 2 (r.h.s.), we can see that the absorption over continuum contrast varies from 10 ... 20% with the maximum obtained for cold brown dwarfs if SiO_2[s] is present. This contrast is achieved because the grains are small (< 0.2 μm). In the absence of SiO_2[s], Mg_2SiO_4[s]/$MgSiO_3$[s] will absorb weakly at 9.7 μm. In the case of large grains, no feature can be detected and it will not be possible to determine the composition of these grains. The presence or absence of SiO_2[s] can be tested observationally. Recently, Cushing et al. (2006) presented *Spitzer* IRS[2] results showing L-dwarf spectra with a 1 – 1.5 μm broad absorption centered at $\lambda \approx 9$ μm.

[2] $R = 90$ for $\lambda = 5.3 \mu$m ... 15.3 μm

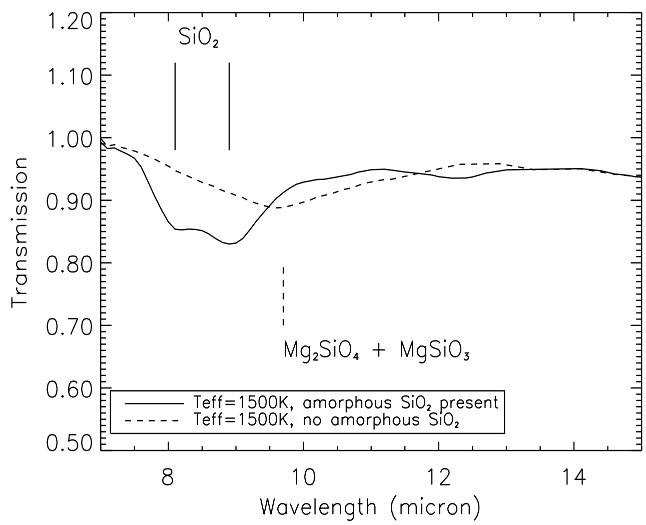

Fig. 2. Absorption transmission spectrum (= $F_\nu/F_{\rm cont}$ with $F_{\rm cont}$ the local continuum flux with respect to the feature) for the model in Fig. 1 with (solid line) and without (dashed line) formation of SiO_2[s]. The absorption feature of SiO_2[s] centered at ~8.7 μm.

However, we have treated an idealized situation where dust grains are the main sources of opacity. In reality, the feature will appear on the top of gas absorption lines. The gas phase absorption proceeds by lines whose width is determined by the pressure at the height of the absorption layer. Typical molecular band widths are ~ 0.1 μm.

Another limitation of our treatment is the assumption of spherical grains which may introduce spurious effects during the opacity calculation. Grains are most likely non-spherical and their absorption coefficients should be computed with, for example, the hollow sphere model (Min et al., 2005) which successfully models asphericity by applying a distribution of hollow spheres. However, the use of hollow spheres will introduce minor changes in the shape of the absorption feature and will not change significantly the wavelength-position of the dust features and hence the conclusion of this paper. Finally, the heterogeneous formation model does not compute the exact grain size distribution but only its moments from which the mean size can be computed. Future work is needed to calculate better analytical representations of the size distribution function from the dust moments.

4. Conclusions

We have studied the dust spectral signatures predicted by the Helling & Woitke (2006) models which make specific observational predictions in terms of grain composition and size at different altitudes. Heterogeneous dust formation in brown dwarf atmosphere results in dusty grains composed mainly of amorphous SiO_2[s] and amorphous Mg_2SiO_4[s]/$MgSiO_3$[s] with impurities of Fe and Al oxides, TiO_2 and MgO. The dust forms one continuous layer in which the grains gradually change composition and size. The grains are sufficiently small in the upper atmosphere to produce solid resonance features in the infrared, a conclusion reached also by Cushing et al. (2006). In contrast, grain composition derived from chemical equilibrium models is dominated by Mg_2SiO_4[s] with the noticeable absence of amorphous SiO_2[s], which is a metastable species. The difference in dust composition allows us to make predictions in dust spectral features in the infrared for the two types of grains. Amorphous SiO_2[s] moves the peak of the absorption to 8.7μm while a nearly pure Mg_2SiO_4[s]/$MgSiO_3$[s] absorbs at 9.7μm with a much smaller contrast. Therefore, infrared features of dust grains could be used to directly detect the presence of dust in brown dwarf atmospheres. The detection of dust absorption features supports the prediction that grains have small size < 0.5 μm and is present in the $\tau_{\rm dust}$ < 1 upper atmosphere.

Acknowledgements. We thank the anonymous referee for her/his suggestion. We thank A. Heras for commends on the manuscript, F. Allard and P. Hauschildt for making their model results freely available. ChH and WFT are/were supported by ESA internal fellowships at ESTEC. PW was supported by the NWO Computational Physics program, grant 614.031.017, in the frame of the AstroHydro3D initiative. The computer support by the ESTEC RSSD computer team is highly appreciated. Most of the literature search was done with ADS.

References

Ackerman, A. S. & Marley, M. S. 2001, ApJ, 556, 872
Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A. et al. 2001, ApJ, 556, 357
Begemann, B., Dorschner, J., Henning, T., et al. 1997, ApJ, 476, 199
Bohren, C. F. & Huffman, D. R. 1983, Absorption and scattering of light by small particles (New York: Wiley, 1983)
Burrows, A., Marley, M., Hubbard, W. B., et al. 1997, ApJ, 491, 856
Cooper, C. S., Sudarsky, D., Milsom, J. A. et al. 2003, ApJ, 586, 1320
Cushing, M. C., Roellig, T. L., Marley, M. S., et al. 2006, ApJ, submitted
Helling, C. & Woitke, P. 2006, A&A, submitted
Henning, T. & Mutschke, H. 1997, A&A, 327, 743
Hofmeister, A. M., Keppel, E., & Speck, A. K. 2003, MNRAS, 345, 16
Jäger, C., Dorschner, J., Mutschke, H., Posch, T., & Henning, T. 2003, A&A, 408, 193
Lodders, K. & Fegley, B. 2005, in press, Review for Astrophysics Update
Lunine, J. I., Hubbard, W. B., Burrows, A., Wang, Y.-P., & Garlow, K. 1989, ApJ, 338, 314
Marley, M. S., Saumon, D., Guillot, T., et al. 1996, Science, 272, 1919
Min, M., Dominik, C., & Waters, L. B. F. M. 2004, A&A, 413, L35
Min, M., Hovenier, J. W., & de Koter, A. 2005, A&A, 432, 909
Ordal, M. A., Bell, R. J., Alexander, R. W., Long, L. L., & Querry, M. R. 1985, Appl. Opt., 24, 4493
Ribarsky, M. W. 1985, in Handbook of Optical Constants (ed. E. D. Palik (Orlando: Academic Press, 1985)), 795
Rietmeijer, F. J. M., Nuth, J. A., & Karner, J. M. 1999, ApJ, 527, 395
Tsuji, T. 2002, ApJ, 575, 264

Tsuji, T., Ohnaka, K., Aoki, W., & Nakajima, T. 1996, A&A, 308, L29
Woitke, P. & Helling, C. 2003, A&A, 399, 297
Woitke, P. & Helling, C. 2004, A&A, 414, 335